DOCUMENT RESUME

ED 061 600 EA 004 186

TITLE	Air-Supported Structures.
INSTITUTION	Ontario Dept. of Education, Toronto. School Planning and Building Research Section.
PUB DATE	Mar 72
NOTE	16p.
AVAILABLE FROM	School Planning and Research Section, Ontario Department of Education, 14th Floor, Mowat Block, Queen's Park, Toronto 182, Ontario (Canada) ($1.50)
EDRS PRICE	MF-$0.65 HC Not Available from EDRS.
DESCRIPTORS	*Air Structures; Bibliographies; *Building Design; Building Materials; Doors; Flooring; Mechanical Equipment; *Physical Facilities; *Spatial Relationship; *Summative Evaluation

ABSTRACT

This study has been prepared to set out some of the benefits and the problems involved in the use of air-supported structures. Also indicated are the types of inquiries that should be made when the use of such structures is being considered. Technical and engineering details, such as the properties of various fabrics, are not included. (Author)

ED 061600

Air-Supported Structures

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Prepared by
School Planning and Building Research

March, 1972

Architectural Services
School Business Administration Branch
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1

Preface

During the past few years, the potential of air-supported structures has caught the public's imagination. A great deal of discussion has ensued regarding the use of such buildings to house educational facilities. This form of structure has a number of features and problems which make it somewhat unique among buildings. Some of the characteristics of the air-supported structure, such as a large, clear-span volume and low capital costs, are the basis for suggesting it as a valid solution to certain building problems. On the other hand, there are features, including solar heat gain, acoustic patterns, and high operating costs, which rule out its use in other circumstances. The advantages and disadvantages of the air-supported structure must be evaluated in the light of the determinants of each particular situation.

Because air-supported structures are still in the developmental stage, their characteristics change as technological advances occur. For example, new long-life skins and air-conditioning are now being tested. Also, building codes and regulations governing the use of this type of facility are being introduced.

The study has been prepared with a view to setting out some of the benefits and the problems involved in the use of air-supported structures and to indicating the type of inquiries that should be made when considering their use. Technical and engineering details, such as the properties of various fabrics, are not included. To be sure of obtaining the specific details of the latest developments, those seeking such information should contact recognized experts in the field.

2

Contents

Introduction	4
The Principle	4
Foundation	6
Floor	7
Fabric Envelope	7
Mechanical Equipment	9
Heating	9
Lighting	10
Door	11
Cost	12
Summary of Advantages and Disadvantages	12
Survey of Opinions from Owners and Users of Existing Air-Supported Structures	14
Appendix	15
Bibliography	16

Introduction

The air-supported structure is a "building" that is solely supported and stabilized by the internal inflation pressure. A continuous supply of air is needed to maintain the required pressure inside the structure because of air losses through leakage in construction, entry doors, and ventilation outlets. Because of their external appearance, air-supported structures are often referred to as "bubble structures". Pneumatic structures composed of air beams, air arches, air ribs, or air pillows are sometimes called "air-inflated structures". In Canada air-inflated structures are uncommon and therefore are not dealt with in this publication.

According to the article entitled "Air-Supported Structures" by D. A. Lutes in the Canadian Building Digest, an air-supported structure might be defined as a single wall or balloon-like structure filled with air maintained at a pressure slightly above ambient. Air-inflated structures might be defined as double-wall structures where the skin is shaped into tubular or cellular compartments pressurized to develop structural stiffness. The usable space, in contrast, is not pressurized.

Air-supported structures are growing in popularity. To be used effectively, air-supported structures must be selected for their suitability rather than for their novelty. Therefore it is important to rationally evaluate the benefits and problems inherent in this form of construction. The working principle of the structure is very simple, but it has factors that are unconventional in terms of construction, use, operation, and maintenance. As each proposed air-supported structure will pose unique problems, every proposed application must be thoroughly investigated in terms of these particular design parameters.

The Principle

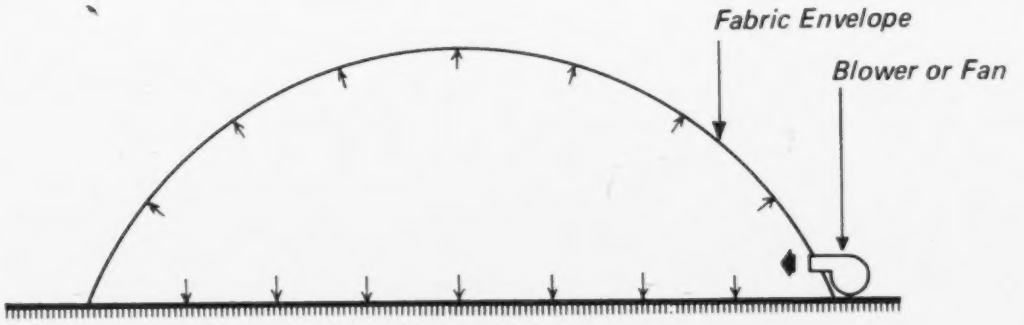
The air-supported structure is comprised primarily of a fabric envelope having its edges anchored to the ground and its shape maintained by means of internal pressure. Air is introduced into the enclosed space by mechanical means. Because the anchorage forms an airtight construction, the air introduced gradually builds up a pressure which inflates the fabric envelope to its designed shape. In general, the anticipated pressure is 1 in. of water column, which is sufficient to withstand a windstorm of 60 to 70 mph.

Although the construction is airtight, it is not airproof. A certain leakage is expected. Entrances and ventilation outlets also cause air loss. Therefore, the air-handling equipment must provide a continuous supply of air into the structure to maintain the pressure. If the equipment fails to function, the structure will collapse gradually; a sudden collapse will not occur. There have been numerous simulation tests on the collapse of an air-supported structure such as the opening of a door and/or the discontinuation of the air supply. The results show that the air-supported structure can be evacuated satisfactorily and safely. In a case where a door (3 ft. x 6 ft. 8 in.) was kept open, the pressure dropped from 1 in. of water column to 0.1 in., but the structure remained inflated with the blowers on. When the blowers were turned off, it took five minutes for the bubble to settle to about 7 ft. from the ground.

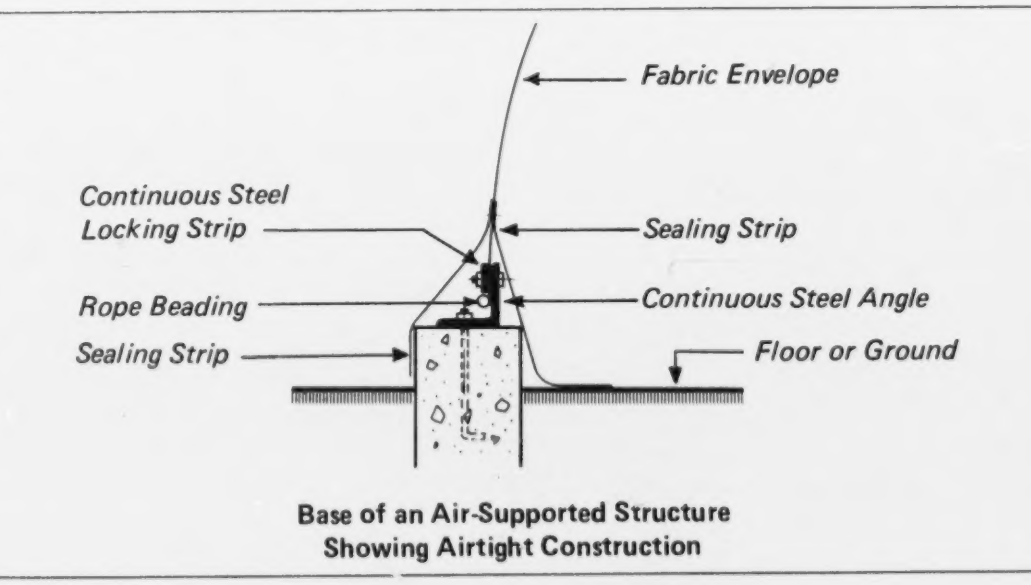
There is no theoretical limit to the size of the fabric envelope, but there is a practical limit to the mechanical equipment. The heat loss and air supply requirements are not directly proportional to the square footage of the structure. They become disproportionately large with bigger structures. One opinion suggests that the 45,000 sq. ft. bubble structure at Harvard University, Cambridge, Massachusetts, is about as large as one should consider.

The height of an air-supported structure is a factor to be considered. A low structure is good for wind stability and requires

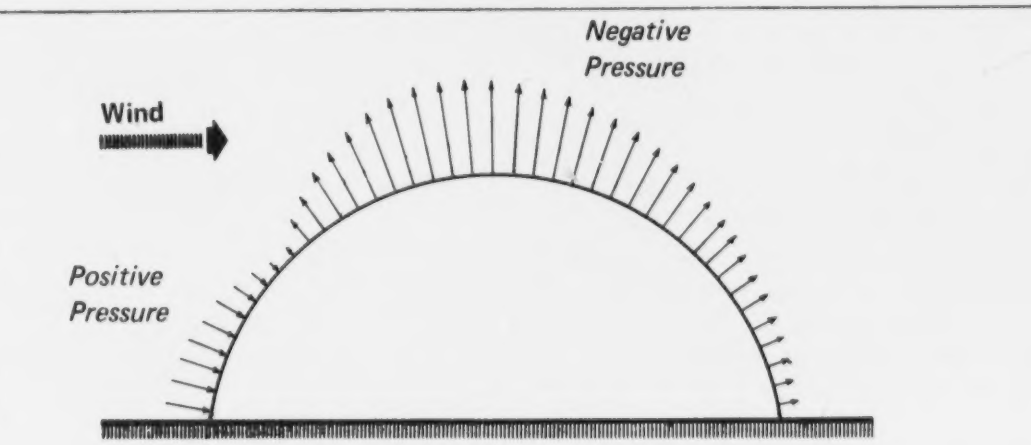
relatively less internal air pressure to withstand high winds, but allows snow to accumulate more readily. Conversely, a tall structure is more sensitive to wind disturbance and requires a much higher internal air pressure to maintain stability, but it allows snow to slide off. Therefore the optimum height should be established by a compromise between wind and snow effects. It should also satisfy the functional space requirements of the structure. Most air-supported structures appear to have a semi-circular cross section, but the heights of large structures are proportionally lower.



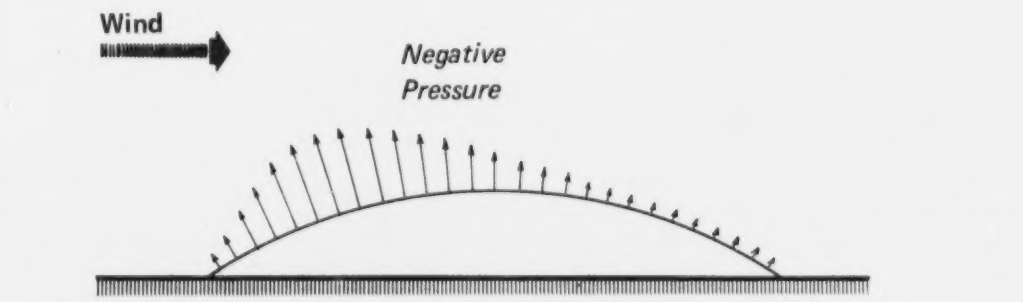
The Principle of the Air-Supported Structure



Base of an Air-Supported Structure Showing Airtight Construction



Wind Effect on High Structure



Wind Effect on Low Structure

5

Foundation

The foundation of the air-supported structure is not designed to be load-bearing. Its purpose is to provide weight so as to prevent the structure from "flying away" when subjected to the action of the wind and its own internal air pressure. Perhaps the term "foundation" should not be used since the fabric envelope can be anchored or fixed into position by other means without actually having the conventional type of foundation wall and footing.

In all cases, it is important to recognize the nature of the soil and the foundation design. It is strongly recommended that the professional services of a soil consultant be used; the foundation is not an area where economies should be sought.

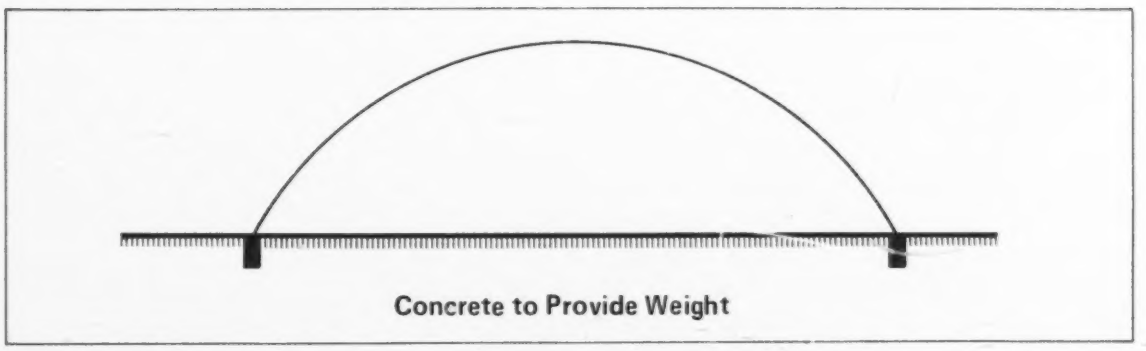
A concrete foundation is structurally more rigid and has no limitations when compared with other methods, but it is impractical to relocate. It therefore limits the relocatable aspect of the fabric envelope. In the case of expansion, the concrete foundation will have to be extended before an addition to the fabric envelope can be made.

Depending on the nature of the soil, the concrete foundation can sometimes be designed to provide weight not just by means of its own weight, but also the weight of the soil above it. This can eliminate the massiveness of the concrete work, but it requires more extensive excavation.

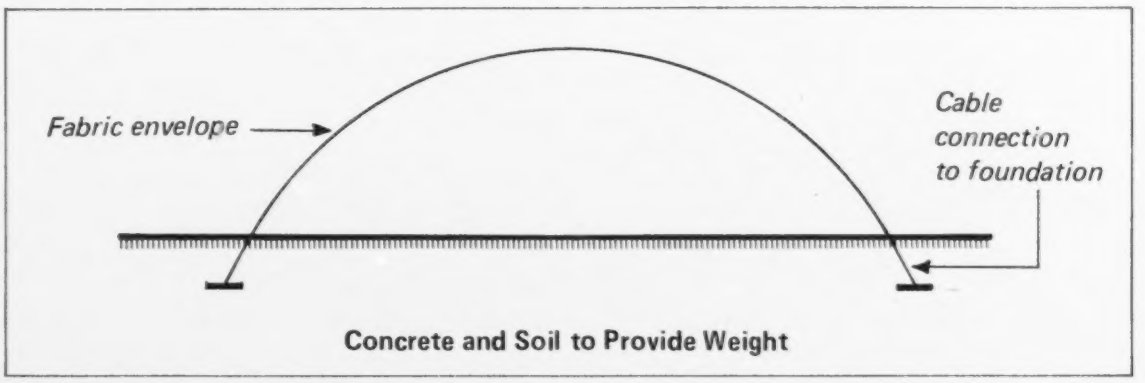
In lieu of the concrete foundation, weight can be achieved by means of using ballast. Although this method involves certain limiting factors such as the size of the air-supported structure and reliance on the availability of local ballasts, it provides greater potential portability. The common types of ballasts are sandbags, concrete blocks, and water tanks.

Instead of relying on the weight of the heavy or special foundation, the fabric envelope can be anchored to the ground by means of earth anchors, mechanical devices, or patented systems. However, these depend on soil conditions and should not be used without the advice of a soil consultant.

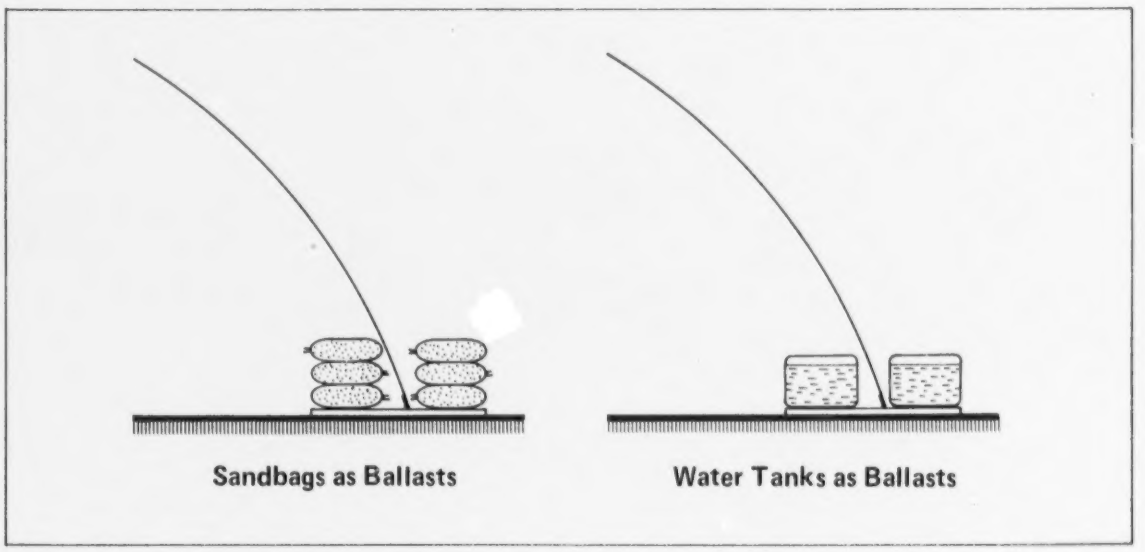
The success of this kind of application depends on the type of anchors, soil conditions, and engineering techniques. It is intended to save construction time and cost. It provides a greater degree of portability and allows expansion of the air-supported structure with minimum cost.



Concrete to Provide Weight

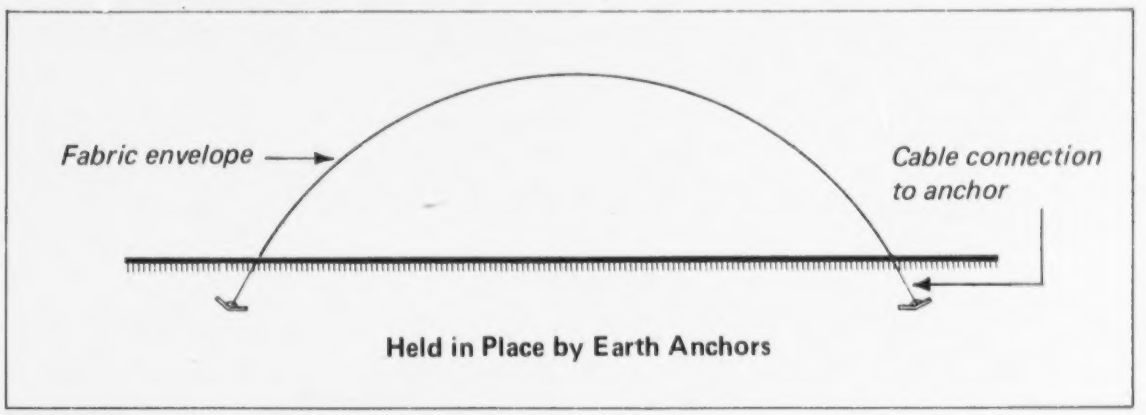


Concrete and Soil to Provide Weight



Sandbags as Ballasts

Water Tanks as Ballasts



Held in Place by Earth Anchors

Floor

A reasonably flat site is all that is required for the erection of an air-supported structure. Depending on the intended use, the bare ground may even form the "floor". The concern here is not the constructional aspect but the practical aspect. Grass, for instance, will not grow inside the structure if the fabric envelope is of the opaque type.

Conventional floor construction and finishes may be used if an air-supported structure is to be deflated seasonally and the envelope stored, but both the construction and the surface must be suitable for external exposure. Otherwise, the finished floor will have to be protected at the expense of increased maintenance costs. If the structure covers a swimming pool, the removal of the envelope in the summertime is clearly beneficial.

The choice of floor covering depends on the type of function to be housed and on whether or not the covering is also intended for exterior use.

Fabric Envelope

The fabric envelope forms the "superstructure" of the building, serving both as roof and walls. Fabric materials commonly used are made from synthetic fibres such as nylon, polyester, glass fibre, and polypropylene. Normally, the fabric is chemically coated with vinyl to resist weather, fire, fungus, and chemical action.

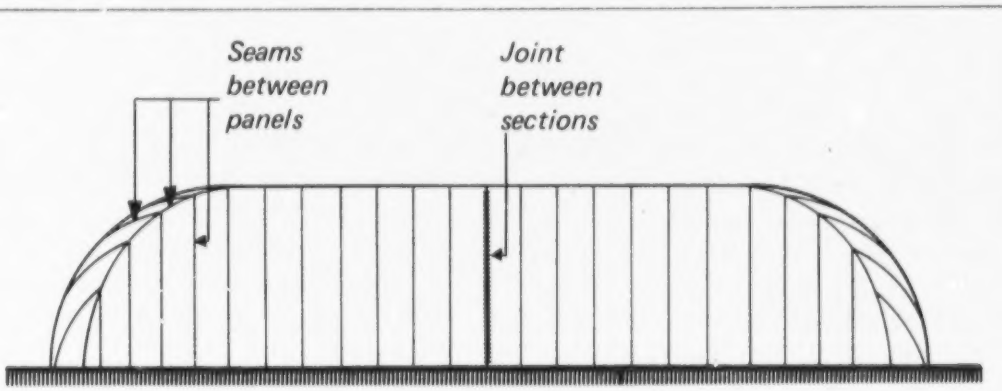
The coated fabrics have been well tested in recognized laboratories for strength, effects under extreme temperatures, flame resistance, resistance to tear and subsequent propagation, watertightness, dampness and so forth. The life span of fabric envelopes currently available on the market ranges from roughly five to ten years depending on the material and coating of the fabric and on the length of exposure to the weather. There are reported cases of fabric envelopes lasting over ten years. The fabric deteriorates more rapidly if it is left in place during the summer months.

The fabric envelope is not woven in one piece but is composed of a number of panels permanently joined together by various methods such as electronic welding, sewing, and cementing. While electronic welding is considered the most durable fabrication method, improved methods are constantly being researched. Although pieces of the fabric panels can be joined together to form the entire envelope, it is preferable to sectionalize the envelope for easy handling, particularly if the envelope is large. Examples of sectionalized envelopes:

	Floor Area	*No. of Sections*
Humber College of Applied Arts & Technology	*19,096 sq. ft.*	*2*
Trent University	*23,000 sq. ft.*	*3*

The joints between the sections are not permanently bonded together like the seams of the panels, but are "fastened" according to the interlocking system of the manufacturer, so that they can be assembled or disassembled in the field. A sectionalized envelope has the following advantages:

- Ease of assembly and disassembly
- Easy storage and transportation
- Easy expansion. Additional sections can be added when expansion is required.
- Easy repair in the event of serious damage, only the section involved need be returned to the factory for repair. If the damage is too serious for repair, only the damaged section need be replaced.



Side View of Air-Supported Structure

Manufacturers offer a standard range of sizes suitable for enclosing large space facilities such as tennis courts, basketball courts; skating rinks, swimming pools, or running tracks. Most manufacturers have options on custom sizes without an appreciable increase in cost.

Fabrics are either translucent or opaque. By combining translucent and opaque fabrics the envelope can be tailored to produce a variety of lighting conditions. For example, experience shows that there is little or no contrast between the tennis balls and the white translucent fabric envelope that covers the tennis courts. This problem can be alleviated by putting a band of dark-coloured opaque fabric around the base of the envelope stretching from ground level to the playing height.

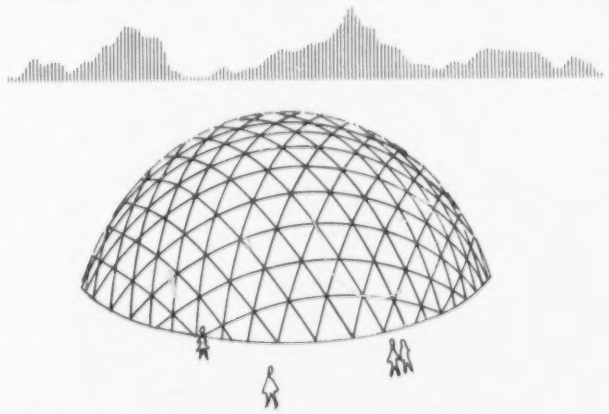
If windows are desired, flexible, transparent plastic sheets can be incorporated into the fabric to act as windows. Of course, such windows cannot be opened. It is important to be aware of the disadvantages of incorporating a kind of plastic into the fabric whose lifespan and performance do not match those of the fabric. Some types of plastic gradually turn yellow and produce distorted images. Some even crack. Generally such materials are structurally weaker than the main fabric. Therefore the problem of compatibility between different materials must be carefully examined.

Having a weight of about 0.2 lb/sq. ft. and a thickness of about 1/32 in., the fabric has practically no thermal insulation value. This means that heat loss is very great in the winter. This heat loss, however, is needed to melt snow which may accumulate on top of the envelope. The melted snow forms a film of water on the fabric which causes newly fallen snow to slide off. Should the insulation value of the fabric be improved (either by means of its own chemical and physical structure or by means of attached liners), the air-supported structure would collapse under a heavy accumulation of snow. This is a dilemma.

Solar heat gain in the summertime is also a serious problem. A maximum number of air changes per hour will be needed to cool the structure. One case study shows that approximately eight air changes per hour are needed to keep the inside temperature down to about 14°F ***above*** the outside temperature. Spraying water over the fabric will cool the structure more effectively resulting in an inside temperature of about 4°F ***above*** the outside air temperature. Water cooling requires a more complicated installation, involving perforated hoses mounted on the envelope, connection to a water supply, and proper drainage. Traditional air-conditioning systems are prohibitively expensive to operate due to the tremendous solar heat gain.

The use of cables to reinforce the fabric envelope is relatively new, the practical performance of which has yet to be evaluated. Theoretically, the cable system has the following advantages:

- By breaking up the symmetry of the fabric surface, the acoustics are improved.
- By minimizing stress on the fabric, a lighter and more economical fabric (1 ply instead of 2 plys) may be used. The replacement cost of the fabric envelope will therefore be less.
- Cables may permit the hanging of lighting fixtures, a thermal liner, an acoustic liner, or curtains to serve as "partitions". (However, it should be remembered that such weight imposed on the cables or the envelope will reduce the ability of the structure to withstand an equal amount of positive wind load and snow load.)



An Air-Supported Structure With Cables to Reinforce its Fabric Envelope

8

Mechanical Equipment

Heating

Essentially a fan or a blower is needed to maintain a steady supply of air in the structure and compensate for air loss through leakage, ventilation, and the opening of doors for entry and exit. The leakage may be as much as 10 cu. ft. per minute per linear foot of the envelope base, depending on the tightness of the installation. A dual fan or blower system is recognized as the minimum requirement. Each unit must be capable of handling the normal air loss and supplying the required amount of air. Only one unit is normally used; the other serves as an emergency standby. This emergency unit is designed to operate automatically if the other shuts down. Both units operate simultaneously during the inflation of the structure to minimize erection time. The minimum requirement also includes an engine-driven electric generator capable of automatic self-starting and powering one or both fans or blowers in the event of a power failure.

Heating units are incorporated in the mechanical system. The installation costs are low because no duct work is used. The forced-air system provides a nearly instantaneous response for warming up because there is no mass (walls, roof, etc.) to heat.

The mechanical equipment is located outside the structure. Generally, its design does not require the protection of a shelter, but this may pose a problem aesthetically. A controversial principle of aesthetics suggests that if the parts of the equipment are properly articulated and coloured, it can create a pleasing form of its own. The conventional viewpoint, on the other hand, demands that the equipment be housed. Whatever the method used, most existing air-supported structures are faced with the problem of unsightly mechanical equipment.

The cost of operating the heating system is a significant expenditure which should be carefully evaluated before deciding to build an air-supported structure. The thermal resistance of the fabric is almost nil, and thus the overall heat transfer coefficient (U factor) depends primarily on the exterior and interior surface-air films of the fabric. The U factor is the rate of heat flow through a medium of single or composite materials. It includes the thermal resistance of the surface-air films on both sides of the medium. It is expressed in BTU per hour passing through each square foot of the medium for every Fahrenheit degree temperature difference between the two sides of the medium. (BTU/hr./sq. ft./°F).

U Factors of Common Media

	U factor
Fabric	*1.05 approx.*
Double-pane window	*0.55*
Average conventional wall	*0.10*

The following hypothetical analysis compares the heat loss of an air-supported structure and a conventional gymnasium building. Note that the heat loss of the air-supported structure by conduction is 4.7 times more than that of the conventional building. The heat loss by ventilation is assumed to be equal in both cases (See Appendix).

When an ordinary building is not in use, the general practice is to lower the temperature somewhat and stop the ventilation. In the case of the air-supported structure, the temperature may be greatly reduced or even brought down to the same temperature as the outside because the structure can be warmed up again in minutes. However, those who wish to be prepared for unexpected snowfall without taking extra precautions do not favour the lowering of the night temperature. They prefer to maintain the normal or slightly below normal temperature, and save the inconvenience or cost of special surveillance.

If an air-supported structure covers a swimming pool, it will have to be heated even when the pool is not in use in order to maintain the water temperature.

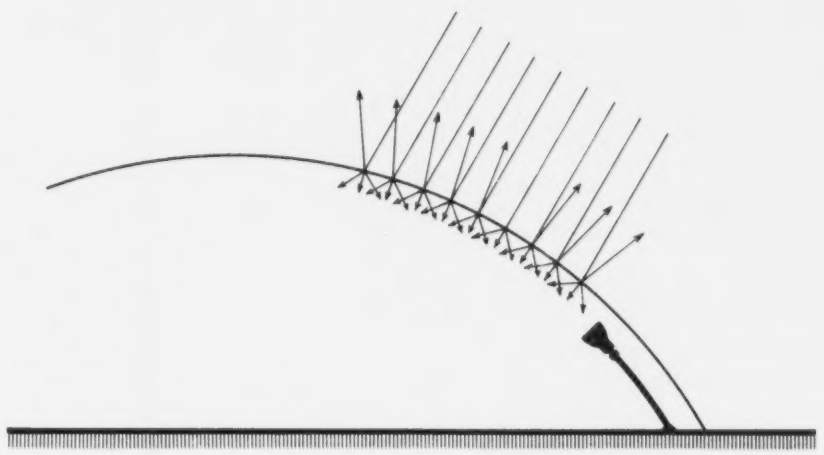
The heating cost of the air-supported structure depends on the climate and the amount of snowfall. It is, of course, greatly influenced by the conditions under which the structure is maintained.

HEAT LOSS COMPARISON

	Conventional Gymnasium	*Air-Supported Structure*
Heat loss by conduction:	*391,850 BTU /hr.*	*1,858,162 BTU /hr.*
Heat loss by ventilation:	*1,206,485 BTU /hr.*	*1,206,485 BTU /hr.*
Total heat loss:	*1,598,335 BTU /hr.*	*3,064,647 BTU /hr.*

Lighting

Because the fabric envelope will not support lighting fixtures, free-standing lampposts are used for this purpose. To minimize the number of posts and fixtures, only high intensity light lamps, such as 1,000 watt mercury vapour lamps, are used. The lampposts are designed to match the curvature of the envelope, and they can be dismantled for relocation. Most fixtures are adjustable and are usually directed upwards to give indirect lighting, necessitating a good reflection from the fabric which should be white or a very light colour. The type of fabric commonly used is white and translucent, through which daylight is diffused into the interior. Although the degree of translucency varies with the fabric used, it is generally insufficient for lighting without the help of artificial lighting. Nevertheless, the translucent fabric plays a part in illumination. It is to be noted that the translucent fabric will allow a certain portion of the artificial light to be diffused outwards just as it allows some daylight to come in. Therefore the efficiency of reflection for indirect lighting is lower than normal. For most sports activities, the design should call for about 30 foot-candles distributed evenly over the entire interior.



Sunlight Diffuses into the Interior

Artificial Light Diffuses Outwards

10

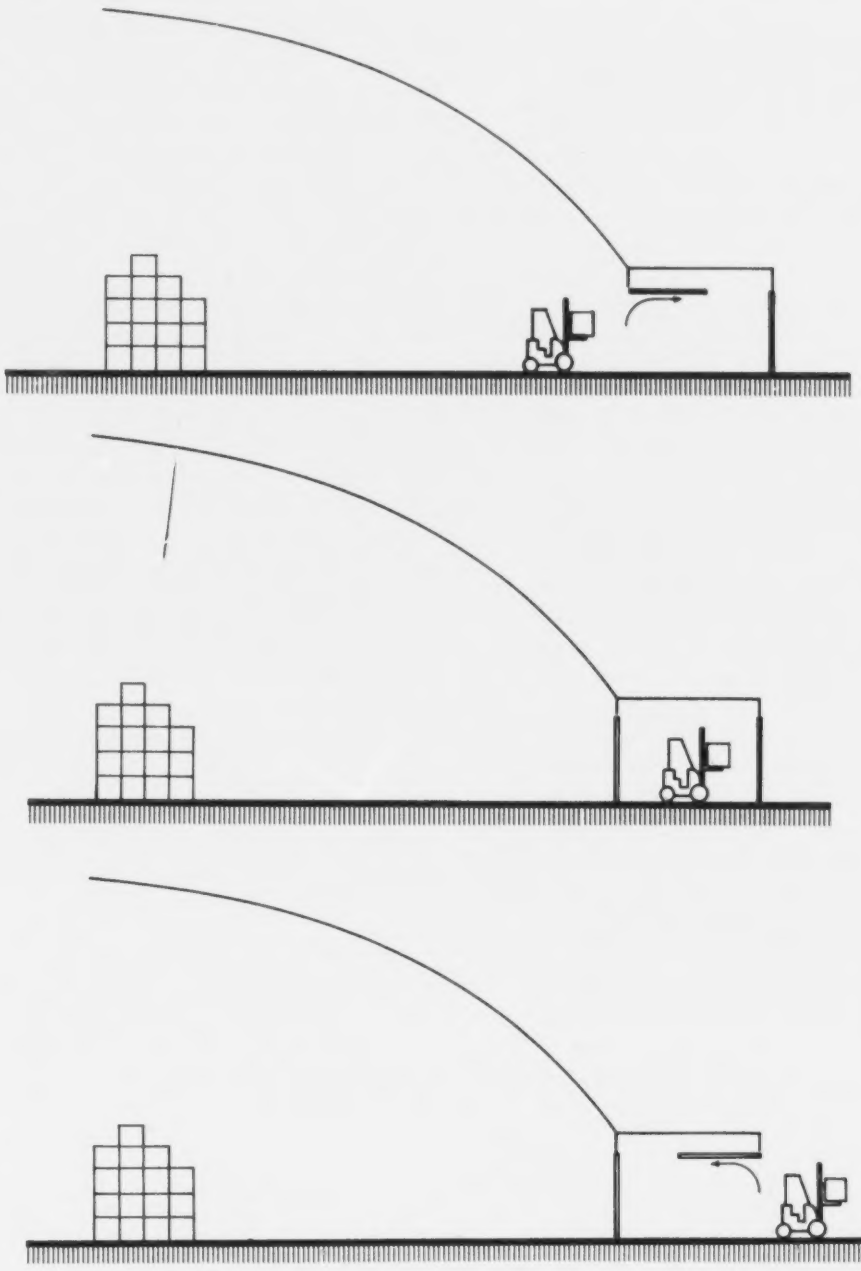
Door

To minimize air loss, only special types of doors can be used. For ingress and egress, revolving doors are ideal,but to comply with fire-safety requirements swing-type doors must also be used, and they have to be pressure-balanced to take care of the pressure difference between the outside and the inside.

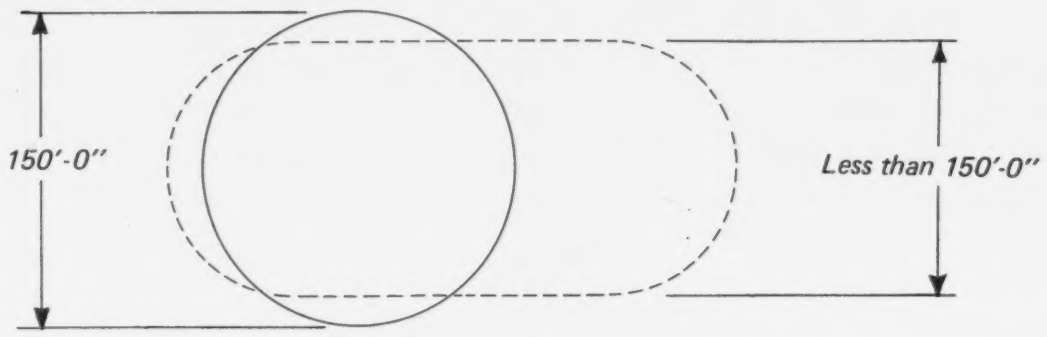
In the case of a warehouse structure, an air lock is necessary for service vehicles or the movement of large equipment. The air lock works like an air trap with a door located at each end. Only one door opens at a time in order to prevent excessive loss of air.

Door frames or any other rigid members must be installed into self-supporting positions structurally independent of the fabric envelope.

Current fire-safety standards limit the maximum distance from any point to the exit door to 75 ft. This suggests that the maximum size of a circular air-supported structure can be only 150 ft. in diameter. In the case of an elongated structure, the dimension across the structure can hardly come close to 150 ft.(See bottom diagram) Fire-safety requirements have therefore limited the size of the air-supported structure at this time.
However, the maximum distance regulation may change after further research.



Working Sequence of Air Lock



Travel Distance and Size of Air-Supported Structure

11

Cost

The unit of cost per square foot for an air-supported structure may be misleading because operating costs are not shown. The analysis below is the cost breakdown on the air-supported structure at Humber College of Applied Arts and Technology in Rexdale. The various construction elements and their percentage of the total cost are indicated.

The analysis shows that the cost of the air-supported structure is about 1/4 to 1/3 that of the conventional building. The mechanical system costs are minimal because it does not require lengthy duct work or pipe work, nor does it require a system of heating units or convectors normally found along the walls of a conventional building. Therefore it has the merit of simplicity. However, it lacks an air-conditioning system as the operating costs are prohibitive.

To acquire an air-supported structure simply because of its low capital cost without considering its operating costs would be unwise. The basis of any sound decision should be the structure's ability to satisfy certain functional requirements which cannot be served by other means.

Of course, low capital cost is a fundamental characteristic of air-supported structures. Manufacturers are now considering the possibility of leasing their air-supported structures instead of selling them, which may prove financially attractive under certain circumstances.

When used for a gymnasium, the air-supported structure needs changing rooms, washrooms, and so forth, which can best be housed in a separate, conventionally built building. The cost per square foot of this conventional building must be included in the total cost of the facility. The cost ratio of about 1 to 4 or 1 to 3 between the air-supported structure and the conventional gymnasium will be altered somewhat when such supporting facilities are taken into account. Nevertheless, the capital cost of the air-supported structure together with the conventional construction of the supporting facilities is still appreciably lower. An air-supported athletic building may be a suitable development when budgetary restraints demand a low initial cost while permitting high operating costs.

Humber College of Applied Arts and Technology, Rexdale
Air-Supported Structure, 154 ft. x 124 ft. (19,096 sq. ft.)

Description	Cost	$ / Sq. Ft. of Floor Area	% of Total Cost
Fabric envelope	*$ 29,435*	*$1.54 / sq. ft.*	*23.3%*
Excavation, Foundation, and anchorage	*9,286*	*0.49 / sq. ft.*	*7.4%*
Sub-floor and finished floor (71% carpet, 29% wood)	*35,167*	*1.84 / sq. ft.*	*27.9%*
Lighting fixtures	*9,135*	*0.48 / sq. ft.*	*7.2%*
Revolving and other doors	*10,025*	*0.52 / sq. ft.*	*7.9%*
Mech. and Standby equip.	*23,575*	*1.23 / sq. ft.*	*18.7%*
Site services	*9,600*	*0.50 / sq. ft.*	*7.6%*
Total	*$126,223*	*$6.60 / sq. ft.*	*100.0%*

Summary of Advantages and Disadvantages

Advantages

1
Low initial cost — The initial cost of the air-supported structure is minimal. It allows a client with a small capital budget to acquire a facility which could not be obtained if conventional construction techniques were employed.

2
Speed of erection — The actual erection of the envelope takes only one or two days. However, additional time is required for the ground work, site services, foundation, anchorage, flooring, and installation of mechanical and electrical equipment. Nevertheless, construction time is brief and only minimal field labour is needed.

3
Ease of deflation, inflation, and repair — Deflation and inflation of the fabric envelope does not require skilled labour. Many existing structures are seasonally deflated and inflated by their own staff or students. A punctured hole takes only minutes to repair, and most air-supported structures come supplied with repair kits. (The repair of a major fault requires skill and special equipment such as that for electronic fabric welding.)

4
Portability — When deflated and packed, the fabric envelope can be stored in a small space or easily transported elsewhere for storage or use. Depending on the size of the envelope, deflation and packing requires one or two days. The bubble at Trent University in Peterborough has 23,000 sq. ft. of floor area. The fabric envelope is in three sections. Each section weighs about 2,500 lbs., the capacity of a small fork-lift truck, and can be packed into a 4 ft.-diameter, 8 ft.-long roll.

5
Adaptability for temporary functions — For temporary use, the air-supported structure has definite physical and financial advantages over a conventional building. A number of manufacturers are now preparing to lease their air-supported

12

structures, which will increase their attractiveness for short term use.

6
Long span and high ceiling — Clear and unobstructed space is an inherent feature of the structure. Conventional long-span and high-ceiling structures are much more expensive. When the intended function demands these structural attributes, the air-supported structure may have a definite economic advantage.

7
Integrated heating, ventilation, and air-pressure system — The integrated system is also an inherent principle. Lengthy duct works and pipe works are not required. The warm-up time of the space is a matter of minutes.

8
Maximum utilization of daylight illumination — Translucency is a characteristic of some kinds of envelope fabrics. Artificial lighting is minimized during daytime use.

Disadvantages

1
Limited portability in certain applications — The degree of portability depends on the type of construction — concrete foundations, conventional flooring such as wood, and site services such as gas and electricity are not portable. In the case of the air-supported structure at Humber College of Applied Arts and Technology, they represent $2.83 / sq. ft. of floor area which is almost 43% of the total gross unit cost.

2
Short life — The fabric envelope has an estimated life of five to ten years, but all other items such as the foundation, flooring, mechanical equipment, and so forth, have the lifespan of a conventional building. This means that the envelope has to be replaced several times in order to match the life of the other components. Therefore the "low initial cost" of the air-supported structure should not be taken at face value.

3
Poor thermal insulation — The cost of heating is a significant factor and should be evaluated against conventional buildings over time. During winter months when the heat is required to melt the snow or to cause it to slide off, a safe level of temperature will have to be maintained at all times at the expense of heating costs. If the bubble is not to be heated during the inactive hours, it will have to be supervised constantly for the dangers of unexpected snowfall. In the summertime, the heat gain of the air-supported structure poses a cooling problem.

4
Acoustic problem — The curved shape of the air-supported structure produces a peculiar acoustic environment. This poses limitations to its use for large gatherings and open-plan arrangements for different groups.

5
Pressure — Although the air pressure in the structure is only 1 in. of water column, some sensitive people feel a slight effect on their eardrums, particularly at the moment of entering the structure. (Trent University frequently operates its bubble at 0.8 in. of water column without any complaints.)

6
Uncertain performance over long-term period — Although the structure has undergone numerous tests by recognized laboratories, many long-term predictions are extrapolated from short-time tests. Some regard this kind of "accelerated test" as of little use while others place great faith in it. Because of the short history of this type of structure in Canada, one is not yet able to demonstrate performance value over time.

7
Limited use — The "1971 Ontario Building Fire Safety Design Standard" has limited the use of air-supported structures to specific functions. Regarding occupancy, the limit is one person per 100 sq. ft. of floor area.

8
Municipal restriction — Some municipal authorities have restricted the use of air-supported structures to only six months of the year, thereby requiring annual deflation. (The bubble at Trent University is on an annual permit, subject to the authorities' examination every year before renewal of the permit. Annual deflation is not required.)

9
Restriction due to wind — In winds of over 40 mph most codes require that the structure be evacuated.

Survey of Opinions from Owners and Users of Existing Air-Supported Structures

Items of Concern	Trent University, Peterborough (100 ft. x 230 ft.)	Toronto Cricket, Skating and Curling Club, Toronto (57 ft. x 114 ft.)
Period of use – permanently inflated or seasonal	*October to May*	*October to April*
Deflation, storage, and re-erection	*The structure is in three sections and is handled by students and staff. It requires some skill on certain mechanical details and crew organization.*	*Handled by staff. There is no storage problem as it can be stored in a 4 ft. x 10 ft. trolley. Deflation takes 1½ days and re-erection, 2 days.*
Maintenance, operation, and repairs	*Maintenance is minimal. It was once slightly damaged in a 50 mph wind, but it was quickly repaired.*	*No special attention is required for maintenance. The repair of a punctured hole is simply a matter of minutes. The average gas heating is about $180 per month. Maximum pressure within the structure is required to withstand a windstorm.*
Coverage by insurance	*Yes, covered like other buildings. The rate is surprisingly low.*	*No difficulty in securing insurance. It has comprehensive coverage.*
Age of structure to date and anticipated period of use	*Built in December 1969 under a five-year warranty. Expected to be used for ten years or longer.*	*Four years old. Anticipate trading it for a larger structure. The manufacturer is willing to accept the existing structure as a trade-in.*
Is it subject to any local regulations?	*The permit is on an annual basis, subject to renewal every year.*	*Deflation required by North York regulations – six months a year for the first two years.*
Is there any other limitation such as number of occupants?	*100 sq. ft. per person for participants. There are no spectators yet.*	*It is used freely by the tennis players.*
Would you purchase an additional air structure should conditions and requirements warrant it?	*Yes.*	*Thinking of trading for a larger air-supported structure.*
General reaction of owners and users	*Good to satisfactory.*	*Excellent, everybody is pleased.*

Additional Comments by Trent University

Our bubble structure is not a gymnasium; it is a field house, suitable for many sports but not all. Our inside temperature, which is maintained at 55° – 60°F, is satisfactory for active sports, but not high enough for all sports. Although the bubble structure is not expected to perform like a conventional building, it provides a quick, low-cost, and usable building. In order to ensure successful use, we involved students in much of the initial erection and subsequent put-up and take-down work each spring and fall. One of our better decisions was the choice of a light green, semi-translucent fabric which gives us a light, airy, and fun atmosphere inside the bubble. We feel that this is better than the two-colour design (dark-coloured fabric at the floor level up to about 10 ft. with white translucent fabric above) for atmosphere and just as good as the dark fabric in providing the necessary contrast for tennis balls.

The other things that we stressed were the need for cleanliness and adjacent change rooms. We saw one sports bubble elsewhere where the floor was dirty. It was poorly drained and rather flooded when it rained. There were no change rooms within 500 ft. As a result, the students didn't help to take care of it and they didn't like it.

We have a few problems with our bubble. Our lighting should have been brighter. Some janitorial problems have reappeared from time to time. On two occasions, the malfunction of equipment has nearly caused major loss. All of which emphasizes the continuing need for extra surveillance and work when using a bubble. The price of success is a lot of both.

Appendix

Toronto Lawn Tennis Club, Toronto (112 ft. x 114 ft.)

October to May

The Club has no storage space. A small crane is required to lift it into a truck for storage elsewhere, but it is very compact when deflated and requires no skilled labour. The mechanical equipment remains in the field.

The maintenance consists of checking the pressure and testing the emergency standby unit periodically. Once in a windstorm the structure was deflated because of an opened door. The fabric was then punctured by a lighting fixture. The manager's recommendation is that objects liable to puncture a deflating structure should be avoided within the structure.

Yes

Built in February 1969. Expected to be used as long as it will last.

Deflation required for six months of the year.

Occupancy determined by the Ontario Fire Marshal.

Yes.

Very good for the purpose.

Gymnasium

Hypothetical data

Dimensions (inside)	*154 ft. x 124 ft.*
Height of building	*20 ft.*
Clear ceiling height	*18 ft.*
Floor area (net)	*19,096 sq. ft.*
Roof area	*19,096 sq. ft. (approx.)*
Area of walls (85%)	*9,452 sq. ft. (approx.)*
Area of windows (15%)	*1,668 sq. ft. (approx.)*
Outside air temperature	*0°F*
Temperature of ground beneath floor (assumed)	*32°F*
Average inside temperature	*65°F*
U factor of walls and roof	*0.10*
U factor of double-pane windows	*0.55*
U factor of floor	*0.24*
Ventilation *	*6 air changes / hr. (3 outside, 3 inside)*
Volume of interior space	*343,728 cu. ft.*

Result from calculation

Heat loss through walls	*61,438 btu / hr.*	
Heat loss through windows	*59,631 btu / hr.*	
Heat loss through roof	*124,124 btu / hr.*	
Heat loss through floor	*146,657 btu / hr.*	
Total heat loss by conduction	*391,850 btu / hr.*	*391,850 btu / hr.*
Heat loss by ventilation *		*1,206,485 btu / hr.*
Total heat loss (conduction and ventilation)		*1,598,335 btu / hr.*

Air-supported structure

Hypothetical data

Dimensions	*154 ft. x 124 ft.*
Height at centre	*35 ft. 9 in.*
Floor area	*19,096 sq. ft.*
Area of fabric envelope	*25,077 sq. ft.*
Outside air temperature	*0°F*
Temperature of ground beneath floor (assumed)	*32°F*
Average inside temperature	*65°F*
U factor of fabric (assumed)	*1.05*
Ventilation *	*1,031,184 cu. ft. / hr.* *

Result from calculation

Heat loss through fabric envelope	*1,711,505 btu / hr.*	
Heat loss through floor	*146,657 btu / hr.*	
Total heat loss by conduction	*1,858,162 btu / hr.*	*1,858,162 btu / hr.*
Heat loss by ventilation *		*1,206,485 btu / hr.*
Total heat loss (conduction and ventilation)		*3,064,647 btu / hr.*

***Remarks**

The heat loss through ventilation is taken as the heat required to warm the outside cold air according to the practical rate (three air changes per hour) assumed for the conventional building. This poses a difficult problem for comparison, because the air-supported structure has a volume of about twice as much and does not rely on this method of ventilation. For the purpose of this comparison, the rate of ventilation in cubic feet per hour is considered to be equal to that of the conventional building; however, it is to be noted that the realistic rate of the air-supported structure will be less, and in some cases, only 30 cfm / person is recommended. In most cases, the low occupancy does not require the high rate of six air changes per hour (three from outside, three from inside). In order to keep the comparison simple, the loss of air due to leakage is excluded in the calculation.

15

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Acknowledgements

D. F. Aldridge, Architect, University of Toronto

N. B. Hutcheon, Director of Building Research, National Research Council of Canada

D. A. Lutes, Research Officer, Division of Building Research, National Research Council of Canada

M. J. O'Brien, Operations Engineer, Trent University

R. R. Philippe, Office of the Fire Marshal

G. Schindler, Construction Superintendent, Humber College of Applied Arts and Technology

16